Experimental Study of Compaction Creep Model of Broken Rock

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Abstract

By MTS rock mechanics test system, the creep experiments at five stress levels were carried out for the water-saturated broken rock and the natural water-content broken rock with the same mass and different initial stacking density, and the displacement-time curves corresponding to these two samples have been obtained. Fitting the strain-time curves with Kelvin-Volgt creep model, we have got the creep parameters at each stress level. The results indicate that some factors such as compressive stress, initial stacking density and hydrous have distinct effect on the creep parameters. At lower stress level, owing to the existing of the internal pore water, the instantaneous elasticity modulus of the saturated broken rock is slightly lower than that of the natural water-content broken rock; while at the higher stress level, with the discharge of pore water, the instantaneous elasticity modulus of the sample with the bigger initial stacking density is also higher. Under the same stress level, the limit creep modulus of the natural water-content broken rock is higher than that of water saturated broken rock, but the viscosity coefficients of the these two samples have little difference.

Keywords

Saturated Broken Rock; *Natural Water-Content Broken Rock*; *Creep Model*; *Experiment Study*; *Limit Creep Modulus*

Introduction

In mining engineering, the compaction deformation properties of broken rock caused by mining have a great significance in predicting the surface subsidence and in analyzing the shifting law of the overlying strata and migration law of liquid and gas in the broken rock. The compaction deformation of the broken rock is affected by many factors such as the compressive stress, the rock category, the breakage degree, stacking density and hydrous state, which leads to the great difference in compaction property of broken rock.

So far, a lot of research has been done on the compaction of the broken rock. Miao (1997) studied the swell and compaction properties of the broken coal and obtained the curves of compressive stress changing with swell coefficient and of the compaction deformation changing with lateral stress; and Zhang (2005) drew a conclusion by the compaction experimental study of the granular rock that the breaking rate is the biggest when the relative pressure is between 0.5 and 0.6, and the grading curve after crushing can be fitted with a quadratic polynomial. By the compaction experiment of broken coal, shale and sandstone, Ma (2005) obtained that the curve of the compressive stress and strain can be fitted by a exponential relationship; Jiang(2001) studied the compaction mechanism of broken coal gangue and pointed out that the compaction course can be divided into two stages: crushing compaction stage and consolidation compaction stage; while Guo(2002) studied the deformation property of cracked rock in goaf and obtained the distribution law of swell coefficient for the cracked rock in goaf during long wall mining process; and Xu (2011) studied the deformation properties of backfill body during gangue-fly ash filling mining and obtained the best ratio of gangue-fly ash backfill body.

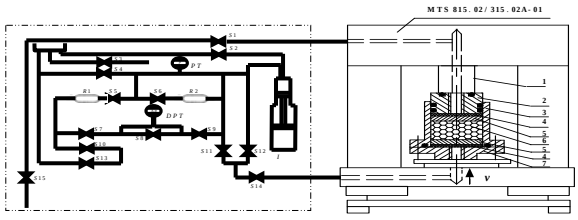
The above studies did not involve the time-dependent deformation of broken rock. In fact, the subsidence above the gob is a slow process which needs to deal with the rock creep. According to statistics, mining subsidence lands of the medium-sized state-owned enterprises in China get up to 84201.4 hm^2 [Guo, 2004]. During mining, with the periodic breaking and caving of overlying strata, the caving broken rock in goaf transit from the natural accumulation state to compaction state, and even if through a long time of natural compaction, the broken rock will experience the second deformation under all kinds of internal and external factors (such as ground stress, ground water

and ground construction loads, and etc). This process is called as old gob activation and can cause a serious threat to the ground buildings, so the gob management often encounters the compaction, seepage and creep problems of broken rock. In recent years, with the promotion and application of green mining technology, the studies about effects of these factors (such as compaction degree of gangue filling, the long term deformation and seepage) on the controlling ground subsidence have become the hot topics in mining engineering [Miao, 2007; Zhang, 2007; Qian, 2008]. According to the existing references, many experimental studies have been done on the creep properties of the intact rock [Zhu, 2002; Fan, 2005], but the research on the compaction creep of broken rock (especially with pore pressure or seepage) is very limited and it is mainly concentrated on deformation experiment study of dry rock samples [Cheng, 2004; Liang, 2003], for example, Shen (1998) proposed a three-parameter model of rockfill creep and Cheng (2004) gave a nine-parameter model. The slow deformation of broken rock can lead to the change in its porosity, and Ma(2009) studied the porosity changing with the time during the creep for the broken mudstone with different grain sizes, but failing to give the creep constitutive equation of mudstone.

Based on the above studies, in this paper the compaction creep experiments under five stress levels for saturated broken rock and natural water content broken rock with grain size 10-15 mm were carried out by the MTS test system and compaction/seepage patented device, as a result, the stress-strain constitutive relations during the compaction creep of broken rock were established.

Test Equipment and Rock Sample

As shown in Fig. 1, the test equipment is MTS815.02 rock mechanics test system. Rock sample is 10-15 mm broken sandstone with mass 1700 g. The uniaxial tensile strength of the sandstone core is 57.5 MPa, and its density ρ is 2473 kg/m3 at natural water content.



Note: S1-S15 –switches; R1~R2– reservoir; PT–pressure transducer; DPT–differential pressure transducer; I–pressure intensifier; 1–upper platen for axial loading; 2–piston; 3–cylinder tank; 4–felt; 5–permeable plate with many holes; 6–rock sample; 7–base plate

FIG. 1 MTS 815.02 ROCK MECHANICS TEST SYSTEM

Test Steps

- Determine the initial height

Taking the rock sample with m=1700 g into the cylinder tank, according to the height H=180 mm, the total height of piston 110 mm, the height h_1 that the piston head outdoes the cylinder tank, the thickness of the permeable plate h_2=9 mm and the thickness of felt h_3 =3 mm, we can get the initial height h_0

$$h_0 = 180 - (110 - h_1) - 2 \times (9 + 3) = 56 + h_1 \,(\text{mm}) \qquad (1)$$

- Saturate the rock sample

Before the axial loading, the rock sample must be saturated by the test system, but for the natural water content broken sandstone this step does not require.

- Axial force loading

Exert each axial compressive force one by one, all the loading time of each force level is 40 s and the force is not unload when loaded to the next force level. After each level of force has been loaded, it is kept steady, and then rock samples started to creep. Each loading level and its keeping time are shown in Table 1. The MTS system was set up to collect the test data (including the displacement, loads) of rock sample at every 5 s.

TABLE 1 EACH FORCE LEVEL AND ITS KEEPING TIME

load/ kN	Stress /MPa	Keeping time of each force /min
25	$\sigma_1 = 1.97$	15
50	$\sigma_2 = 3.94$	30
100	$\sigma_3 = 7.98$	60
200	$\sigma_4 = 15.79$	120
400	$\sigma_5 = 31.58$	180

- Calculate the macro-strain (logarithmic strain)

According to the collected axial displacement S, we can calculate the stacking height h and compressive strain ε of sample at each moment t,

$$\varepsilon = \left|\ln(\frac{h}{h_0})\right| = \left|\ln(1 - \frac{S}{h_0})\right| \qquad (2)$$

Fitting the $\varepsilon - t$ curve and $\sigma - \varepsilon$ level, we can obtain the creep model parameters of broken rock.

Test Results and Analysis

Displacement-Time Curve of Saturated Broken Rock

The mass m of saturated broken rock is 1700 g; whose initial stack height in the cylinder tank is 102 mm. Because the inner diameter *D* of cylinder tank is 127 mm, we can calculate its initial stack density

$\rho_p = \frac{4m}{\pi D^2} = 1316$ kg/m³. Displacement-time curves of saturated rock sample at 5 levels stress are shown in Fig. 2.

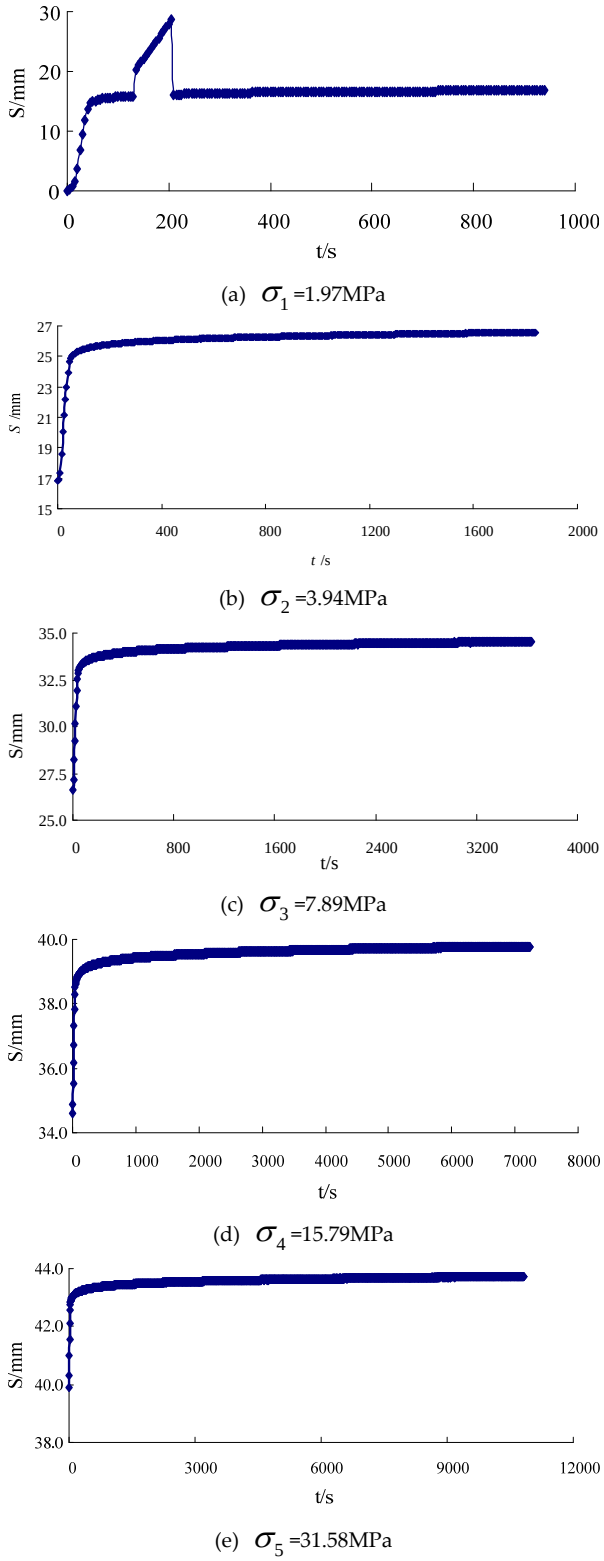


FIG. 2 DISPLACEMENT-TIME CURVES AT EACH LEVEL STRESS

According to displacement-time curves, the deformation of broken rock tends to be stable after a primary creep. Creep curve has a distinct fluctuation at σ_1 =1.97 MPa, resulting from the fact that the position of sample grains suddenly changes under the axial compressive force. The deformations at each level stress include transient deformation at loading stage and creep deformation at stress keeping stage.

Creep Model of Saturated Broken Rock

The common creep models are as follows: Maxwell model, Kelvin model, Kelvin-Volgt model (K-V model), Burgers model and so on, as shown in Fig.3 (a)-(d). Creep in the Maxwell model and Burgers model increase with time and up to infinite. So Maxwell model and Burgers model are liquid models and inconsistent with actual situation of crushed stone, so they cannot be used. Kelvin model cannot reflect instantaneous elastic deformation of material, obviously, inconsistent with elastic properties of the test, so it cannot be used either. Only Kelvin-Volgt model can reflect creep law and instantaneous elastic property. Therefore, the creep of the broken rock has been analysed by Kelvin-Volgt model (K-V model) in this paper.

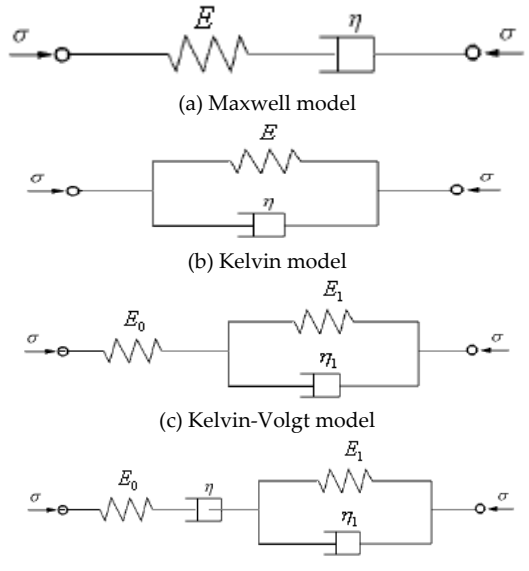


FIG. 3 TRADITIONAL CREEP COMBINATION MODEL

The constitutive form of K-V model is

$$\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E_1}[1 - \exp(-\frac{t}{\tau_1})] \quad (3)$$

Where E_0 is the instant elastic modulus, E_1 is the limit creep deformation modulus, τ_1 is delay time, and

$$\tau_1 = \frac{\eta_1}{E_1} \quad (4)$$

Where η_1 is viscosity coefficient.

The instant elastic modulus E_0 can be determined from stress and elastic strain at loading stage. The data collected in 30 s such as displacement *S*, axial force *F* at the first stress level $\sigma_1 = 1.975$ MPa are as shown in Table 2. Fitting stress-strain diagram drawn by Table 2 we can obtain E0=13 MPa for the saturated broken sandstone at σ_1=1.97 MPa.

TABLE 2 STRESS AND STRAIN AT LOADING STAGE OF σ_1

t/s	*S*/mm	ε	*F* /N	σ /MPa
0	0	0	0	0
5	0.354	0.00347	2775	0.219
10	0.895	0.00882	6061	0.478
15	1.701	0.01682	8770	0.692
20	3.591	0.03584	11673	0.921
25	6.737	0.06833	15365	1.213
30	9.386	0.09653	18831	1.487
35	11.740	0.1222	21997	1.737
40	13.712	0.1443	25272	1.996

Then we calculate creep parameters E_1 η_1. Because instant elastic strain can be expressed as $\varepsilon_0 = \frac{\sigma}{E_0}$, then the limit creep can be expressed as

$$\varepsilon_\infty = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} = \varepsilon_0 + \frac{\sigma}{E_1}$$

So we have

$$E_1 = \frac{\sigma}{(\varepsilon_\infty - \varepsilon_0)} \tag{5}$$

According to the test data, for $\sigma_0 = 1.975$ MPa, $\varepsilon_0 = 0.1443$. When the time attains to 940 s, $\varepsilon / \varepsilon_0 = 1.247$. Let $\varepsilon_\infty = 1.5\varepsilon_0$, we can get E_1 from Eq.(5)

$$E_1 = \frac{\sigma}{(\varepsilon_\infty - \varepsilon_0)} = \frac{1.975}{0.5 \times 0.1443} = 27.35 \text{ MPa} \tag{6}$$

From Eq.(3)we have

$$\varepsilon - \varepsilon_0 = \frac{\sigma}{E_1}(1 - e^{-\frac{E_1 t}{\eta_1}}) \tag{7}$$

Then we have

$$\ln[\sigma - E_1(\varepsilon - \varepsilon_0)] = \ln\sigma - \frac{E_1}{\eta_1} t$$

Let $y = \ln[\sigma - E_1(\varepsilon - \varepsilon_0)]$, $a = -\frac{E_1}{\eta_1}$, $b = \ln\sigma$, Then

$$y = at + b$$

By fitting test data, we have $a = -0.1426$ and $\eta_1 = -\frac{E_1}{a} = 191$ MPa.s.

From the above, we have got E_0 12 MPa, E_1 27 MPa and viscosity coefficient η_1 191 MPa.s for saturated broken sandstone at the first level stress $\sigma_1 = 1.975$ MPa. Accordingly, we can obtain creep parameters of saturated broken sandstone at different stress levels as shown in Table 3, based on which, we have $E_0 = 4.82\sigma^{1.1389}$, $E_1 = 10.05\sigma^{1.3029}$, $\eta = 73.55\sigma^{1.349}$.

TABLE 3 CREEP PARAMETERS OF SATURATED SAMPLE

	σ_1	σ_2	σ_3	σ_4	σ_5
E_0 /MPa	13	20	40	116	281
E_1 /MPa	27	58	135	331	1038
η_1 /MPa.s	191	463	1128	3085	7973

The Displacement –Time Curve of Natural Water-Content Broken Sandstone

The mass of natural water- content broken sandstone is *m*=1700 g, whose initial stacking height in cylinder tank is h_0=106 mm. The corresponding displacement-time curves (*S*-*t* curves) under five stress levels are shown in Fig. 4.

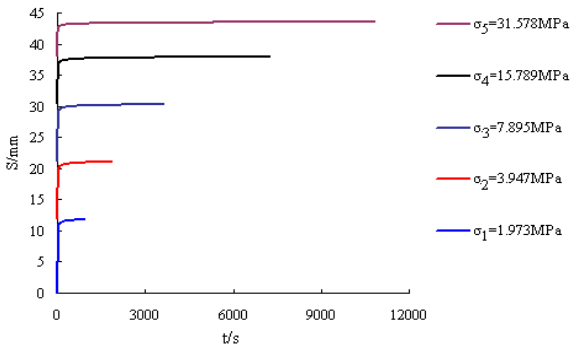


FIG. 4 *S*-*t* CURVES FOR NATURAL WATER-CONTENT SAMPLE

The Creep Parameters of Natural Water-Content Broken Rock

Using the calculation method in the previous section, we can obtain the creep parameters at different stress levels for natural water content broken rock as shown in Table 4, based on which we have

$$E_0 = 7.62\sigma^{0.8797},\ E_1 = 23.97\sigma^{1.197},\ \eta = 213.23\sigma^{1.0311}$$

TABLE 4 CREEP PARAMETERS OF NATURAL WATER-CONTENT BROKEN SAMPLE

	σ_1	σ_2	σ_3	σ_4	σ_5
E_0 /MPa	19	20	37	81	200
E_1 /MPa	50	149	269	579	1613
η_1 /MPa.s	460	842	1717	3501	8069

According to Tables 3 and 4, the $E_0 - \sigma$ curve, $E_1 - \sigma$ curve and $\eta_1 - \sigma$ curve for the above two rock

samples are shown in Figs. 5–7. In Fig. 5, at the first stress level, the instantaneous elastic modulus E_0 of the saturated broken rock is slightly lower than that of natural water-content broken rock, and the existing of pore water is the main reason leading to the decreasing E_0. With the compaction in progress, the pore water in saturated rock sample is drained out, the saturated rock sample is close to natural water–content broken rock; but because the initial stacking density of saturated sandstone is slightly bigger, at the same stress level, its compaction deformation is relatively smaller, so from the second stress level the instantaneous elastic modulus E_0 of the saturated broken rock is slightly larger than that of natural water–content broken rock. From Figs. 6–7, it can be seen that with the increase of stress levels the limit creep modulus E_1 and viscosity coefficient η_1 also increase, and E_1 of natural water-content broken rock is slightly bigger than that of saturated broken rock, but the coefficients η_1 of these two samples have little difference.

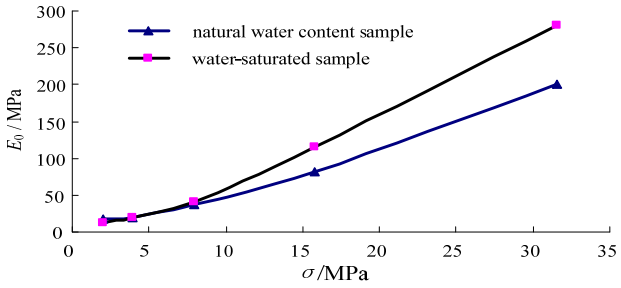


FIG. 5 $E_0 - \sigma$ CURVES OF TWO SAMPLES

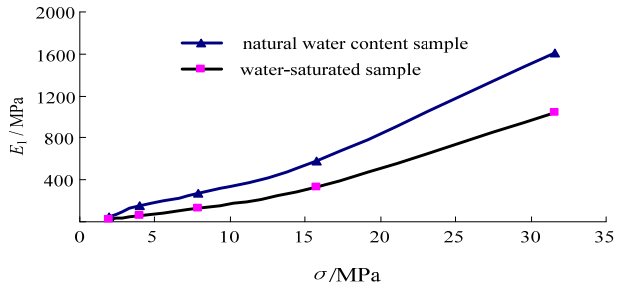


FIG. 6 $E_1 - \sigma$ CURVES OF TWO SAMPLES

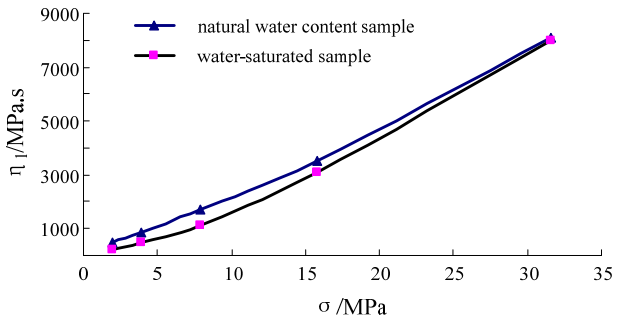


FIG. 7 $\eta_1 - \sigma$ CURVES OF TWO SAMPLES

Conclusions

By MTS rock mechanics test system, the creep experiments under five stress levels for 10-15 mm saturated broken rock and natural water–content broken rock were carried out, consequently, the displacement-time curves and Kelvin-Volgt creep model parameters were obtained. The research indicated that with the increase of the stress levels the creep parameters of the two samples increased markedly; at the same stress level, the saturated broken rock with a higher initial stacking density has a bigger instantaneous elasticity modulus and a lower limit creep modulus, but the viscosity coefficient of the these two samples has little difference.

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References

Cheng Z.; Ding H. "Creep Test for Rockfill." Chinese Journal of Geotechnical Engineering 2004, 26(4):473-476.

Fan Q.; GAO Y. "Experimental Study on Creep Properties of Rocks under Stepwise Loading." Chinese Journal of Geotechnical Engineering 2005, 27(11):1273-1276

Guo G.; Miao X.; Zhang Z. "Research on Ruptured Rock Mass Deformation Characteristics of Long-Wall Goofs." Science Technology and Engineering 2002(2):44–47.

Guo G.; Wang Y.; Ma Z. "A New Method for Ground Subsidence Control in Coal Mining." Journal Of China University Of Mining & Technology 2004, 33(2):150-153.

Jiang Z.; Ji L.; Zuo R. "Research on Mechanism Of Crushing Compression Of Coal Waste." Journal of China University of Mining and Technology 2001, 30(2):139–142.

Liang J.; Liu H.; Gao Y. "Creep Mechanism and Breakage Behaviour of Rockfill." Rock and Soil Mechanics 2003, 24(3):479-482

Ma Z.; Guo G.; Chen R.; Mao X. "An Experimental Study on the Compaction of Water-Saturated Over-Broken Rock." Chinese Journal of Rock Mechanics and Engineering 2005, 24(7): 1139-1144

Ma Z.; Lan T.; Pan Y.; Ma J.; Zhu F. "Experimental Study of Variation Law of Saturated Broken Mudstone Porosity During Creep Process." Chinese Journal of Rock Mechanics and Engineering 2009, 28(7), 1447-1454.

Miao X.; Mao X.; Hu G. "Research on Broken Expansion and Press Solid Characteristics of Rocks and Coals." Journal of Experimental Mechanics 1997, 12(3): 394–399.

Miao X.; Zhang J. "Analysis of Strata Behavior in the Process of Coal Mining by Gangue Backfilling." Journal of Mining and Safety Engineering, 2007, 24(4):379-382.

Qian M.; Miao X.; Xu J.; Cao S. "On Scientized Mining." Journal of Mining and Safety Engineering 2008, 25(1):1-10.

Shen Z.; Zhao K. "Back Analysis of Creep Deformation of Rockfill Dams." Journal of Hydraulic Engineering 1998, 6 (6):1-6.

Su C.; Gu M.; Tang X.; Guo W. "Experiment Study of Compaction Characteristics of Crushed Stones From Coal Seam Roof." Chinese Journal of Rock Mechanics and Engineering 2012, 31(1):18-226.

Xu J.; Zhang J.; Huang Y. "Experimental Research on the Compress Deformation Characteristic of Waste Fly Ash and Its Application in Backfilling Fully Mechanized Coal Mining Technology." Journal of Mining and Safety Engineering 2011, 28(1): 158–162.

Zhang j.; Miao X.; Mao X.; Chen Z. "Research on Waste Substitution Extraction of Strip Extraction Coal Pillar Mining." Chinese Journal of Rock Mechanics and Engineering 2007, 26(s1): 2687-2693.

Zhang Z.; Miao X.; Ge X. "Testing Study on Compaction Breakage of Loose Rock Blocks." Chinese Journal of Rock Mechanics and Engineering 2005, 24(3):451–455.

Zhu H.; Ye B. "Experimental Study on Mechanical Properties of Rock Creep in Saturation." Chinese Journal of Rock Mechanics and Engineering 2002, 21(12):1791-1796